REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	12/18/97	Annual Technical 12/1/96 - 11/30/97

4. TITLE AND SUBTITLE

Atom Interferometry

5. FUNDING NUMBERS

N00014-96-1-0432

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800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

96PR02195-00

11. SUPPLEMENTARY NOTES

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13. ABSTRACT *(Maximum 200 words)*

Atom interferometers, in which atom or molecule de Broglie waves are coherently split and then recombined to produce interference fringes, have opened exciting new possibilities for precision and fundamental measurements with complex particles. The ability to accurately measure interactions that displace the de Broglie wave phase has led to qualitatively new measurements in atomic and molecular physics, fundamental tests of quantum mechanics, and new ways to measure acceleration and rotation:

14. SUBJECT TERMS

DTIC QUALITY INSPECTED 4

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

OFFICE OF NAVAL RESEARCH-N00014-96-1-0432
Atom Interferometery Annual Progress Report
12/1/96-11/30/97
David E. Pritchard-MIT

Atom interferometers, in which atom or molecule de Broglie waves are coherently split and then recombined to produce interference fringes, have opened exciting new possibilities for precision and fundamental measurements with complex particles. The ability to accurately measure interactions that displace the de Broglie wave phase has led to qualitatively new measurements in atomic and molecular physics, fundamental tests of quantum mechanics, and new ways to measure acceleration and rotation:

- Atom interferometers permit completely new investigations of atoms and molecules including precision measurements of atomic polarizabilities that test atomic structure models, determination of long range forces important in cold collisions and Bose-Einstein condensation, and measurements of molecular polarizability tensor components.

- Atom interferometers permit fundamental investigations in quantum mechanics. These include measurements of topological and geometric phases, loss of coherence from a quantum system, quantum measurement, and investigations of multi-particle interferometry and entanglement.

- The large mass and low velocities of atoms makes atom interferometers especially useful in inertial sensing applications, both as precision accelerometers and as gyroscopes. They have a potential sensitivity to rotations $\sim 10^{10}$ greater than optical interferometers of the same area.

- Atom interferometers may have significant applications to condensed matter physics, including measurements of atom-surface interactions and lithography using coherently manipulated fringe patterns that are directly deposited onto substrates.

- Atomic clocks are exquisitely sensitive longitudinal atom interferometers, capable of easily measuring phase shifts due to velocity changes of 1 part in 10^{10}.

Our group has pioneered many of these areas, including the first (and only) atom interferometry experiments that employ physically separated paths to make precision measurements. These investigations have proved to be of wide-spread general interest to the scientific community and have received write-ups in the popular scientific press [1,2].

During 1997, we have made significant progress towards our long term goal of developing further applications and expanding the intrinsic capabilities of atom interferometers. In particular, we have published a paper demonstrating for the first time the remarkable sensitivity of atom interferometers to rotation sensing [3], developed the theory [4] and experimental techniques [5] for a longitudinal atom interferometer, and have made substantial improvements to our apparatus.

I. Longitudinal Atom Interferometry

In interferometry, the central idea is that the various "paths" traversed by waves evolve different phases and result in fringes when interfered. The phase differences can be generated by keeping the wavelength the same and introducing differences in the path lengths, as we have demonstrated in our "transverse" atom interferometer. However, one may also envision keeping the path the same and placing each particle in a superposition of different momentum states. Over the past year, we have developed a theory showing that resonance regions can create and overlap such longitudinal momentum coherences and can serve as atomic beam splitters. An

important implication, therefore, is that Norman Ramsey's Nobel prize winning method of separated oscillatory fields (SOF) may in fact be viewed as a "longitudinal" interferometer. By taking full advantage of the freedom to apply independent frequencies to the resonance regions, we have recently demonstrated a more general configuration - differentially detuned separated oscillatory fields (DSOF). For example, we have performed experiments confirming our prediction that DSOF is a "white fringe" longitudinal interferometer capable of generating and detecting coherences dephased due to the inevitable presence of a distribution of velocities in molecular beams. Several new applications of longitudinal interferometry are described below.

II. Improvements to the apparatus

We have made and are continuing to make several important improvements to our apparatus. Collaborating with H. Smith's group at MIT to fabricate improved atom transmission gratings using holographic lithography, we have demonstrated atom interference fringes (unfortunately with low contrast) using 100 nm period gratings. These gratings give twice the beam separation of our standard 200 nm gratings. We have also significantly upgraded our apparatus. The separated beam atom optical elements have been placed on an optical platform separate from the vacuum envelop which should substantially improve the flexibility of the interferometer as well as its thermal and vibration isolation. The vacuum envelop itself has been replaced by a series of standard 6-way crosses, achieving greater length, facilitating access to the equipment inside the chamber, and permitting the rapid reconfiguration of modular flanges which currently hold the atom optical elements for a longitudinal interferometer. The new apparatus should be very stable and allow the simultaneous pursuit of several different experiments.

III. Ongoing Investigations

<u>Longitudinal interferometry</u>**:** The extension of atom interferometry to include longitudinal coherences represents an exciting frontier. We are currently using the DSOF geometry to measure the longitudinal momentum density matrix of a molecular beam, thereby resolving a long standing controversy concerning the longitudinal momentum structure of atomic beams [6]. The extraordinary sensitivity of longitudinal interferometers to differential changes in velocity of the atom beam can be exploited to detect very small forces. An example is the controversial Anandan force that acts differentially on the components of the wavefunction on opposite legs of a separated atomic beam interferometer [7]. Finally, the techniques developed here will permit implementation of a velocity multiplexing scheme for the precision measurement of large interferometric phase shifts [8,9].

<u>Velocity dependent index of refraction:</u> The physical separation of beam paths in our transverse interferometer permits both amplitude and phase changes in the interference pattern to be observed as one of the interfering atom beams is exposed to some interaction. Using this capability, we recently performed an experiment measuring the index of refraction of various gases and hence the role of atom-atom interactions in collisions [10]. We are planning to extend this experiment to probe for velocity dependencies. There is significant interest in the theoretical community in such results as the interactions are determined by the long range behavior of the atomic potentials; for example, it is predicted that the index of refraction should exhibit Glory oscillations as the velocity of the impinging gas is varied.

<u>Quantum decoherence:</u> Scattering photons from atoms while they are inside an interferometer causes the atoms to change their state. We believe that under suitable conditions, this will not destroy the quantum coherence but rather will cause the atoms to diffuse in momentum space. This experiment is significant since it generalizes our recent realization of Feynman's *gedanken* experiment [11,12] in which decoherence from single photon scattering was measured and then recovered. Also, quantum decoherence is just becoming accessible to study as an important experimental barrier to constructing quantum computers.

Geometric Phases: Precision measurements of the Aharonov-Casher (AC) phase are planned. These will allow a study of the dependence on the interfering particle's dipole orientation for the first time. Modifications made to our interaction region (a device which allows different potentials to be applied to either arm of the interferometer) to introduce spatially varying magnetic fields will permit investigations of Berry's phase as well.

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